PEER-REVIEWED ARTICLE

A Map of the Vegetation of South America Based on Satellite Imagery

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Abstract

We have developed a map of the land cover of South America based largely on NOAA AVHRR LAC (Local Area Coverage) 1-km resolution data. Areas of South America for which there were no LAC data due to cloud cover or other reasons were supplemented with a 3-year time series of 15-km resolution NOAA AVHRR GVI data. Thirty-nine classes were labeled using existing vegetation maps, from phenology, and by visual interpretation of imagery.

We estimated that nine percent of the closed tropical moist forests of South America had been cleared in the decade prior to 1988, the date of the imagery; 22 percent of the original closed forests, which include tropical moist forests as a major component, of South America had been cleared or degraded; 18 percent of the original woodland and 25 percent of the grasslands had been cleared or degraded.

Introduction and Objectives

Human influence is expanding over the surface of the globe, displacing the plant and animal communities that dominated the Earth prior to the emergence of industrial *Homo sapiens*. Reductions in the area of forests are occurring with increases in the area of land in agriculture and in successional or impoverished plant communities (Houghton, in press). More subtle internal changes have been observed in the natural communities around the world as human influences, such as selective tree harvest and toxification by chemicals carried by wind and rain, accumulate (Houghton, 1991; Woodwell, 1990). The extent of the changes in area of major vegetation types, such as forest, savanna, and agriculture, is largely unmeasured, although the potential for measurement using satellite imagery has existed for several years (Woodwell *et al.*, 1983; 1984; Grainger, 1984).

Our purpose is to appraise as objectively as possible the magnitude and significance of the changes underway in major plant communities on a regional and continental scale. Satellite images offer the greatest potential for performing large area, objective appraisals, but the difficulties remain formidable. A useful approach is to develop complete land-cover maps based on aerial photography or satellite imagery. The maps can be widely shared by the scientific community, revised, retested, and compared over time to determine trends and rates of change, and potentially used to monitor compliance with plans, treaties, or laws. We have developed such a map for the land cover of South America using the data from the Advanced Very High Resolution Radiometer (AVHRR) weather satellites of the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce.

The use of satellite imagery to develop vegetation maps is a departure from traditional mapping techniques in that reflectivity and emissivity of plants or of the ground surface are measured from space (Graetz, 1990). A satellite-derived map does not appraise the potential vegetation based on climate, as developed so usefully by Holdridge (1967); nor does it appraise climate based on vegetation, as developed by Köppen (Muller and Oberlander, 1978). A map based on satellite imagery differs from traditional vegetation maps in that it measures a set of characteristics of the Earth's surface different from those used for previous maps. These measurements are different from, and not likely to replace, classical ground-based appraisals of the structure, physiognomy, and species composition of the plant communities. Nevertheless, while ground-based surveys provide details of plant community structure, species composition, and distribution, aerial or satellite surveys offer comprehensive spatial and temporal coverage. Satellite surveys may also yield over the next years increasingly detailed data on plant community composition and structure as new sensors and interpretations are developed.

We have made an effort, outlined below, to compare the land-cover classes discernable in satellite imagery to the vegetation types identified in detailed earlier maps to produce the most detailed continental-scale vegetation map available for South America. The only previous product based on satellite data of South America, of which we are aware, is by Townshend *et al.* (1987) and is based on 4-km resolution Global Area Coverage (GAC) NOAA AVHRR data. In a similar fashion, Tucker *et al.* (1985) produced a continental scale map of Africa with NOAA AVHRR GAC data.

Methods

Sources of Data

The primary data source for this work was the NOAA AVHRR Local Area Coverage (LAC) satellite data. These data have a resolution of 1.1 km at nadir and are available, nominally, for the whole Earth twice daily. They have been supplemented by higher resolution satellite imagery available for certain sections of the continent, by photographs, by earlier maps, and by personal experience on the ground. Because the map produced from the work described here is digital, it has no specific map scale. The scale of a map is determined by the size of the paper map printed. If we were to print the map with each 1-km^2 cell at 1 mm^2, a reasonable choice, the map scale would be 1:1,000,000.

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We have used AVHRR imagery data from the NOAA 9, 10, and 11 satellites. These satellites acquire digital reflectivity and emissivity data from the surface of the Earth in the visible red (0.58 to 0.68 μm), near-infrared (0.725 to 1.1 μm), mid-infrared (3.5 to 3.93 μm), and thermal (10.3 to 11.3 and 11.5 to 12.5 μm) portions of the electromagnetic spectrum (Kidwell, 1988). We used 34 computer compatible tapes, of which the majority were from 1988, the year of primary focus for this project, and from 1987, 1989, 1990, and 1991. With the LAC data acquired, we were able to cover, cloud-free, 69.6 percent of South America. The data were acquired from the U.S. Geological Survey's (USGS) EROS Data Center (EDC) in Sioux Falls, South Dakota.

The EROS Data Center (EDC) converted the 10-bit to 8-bit data and performed radiometric sensor degradation calibration (Holben *et al.*, 1990) on NOAA-9 Channels 1 and 2. Also at EDC, data in Channels 1 and 2 were calibrated using the pre-launch coefficients found in the NOAA Polar Orbiter Data Users Guide (Kidwell, 1988). Each channel (normally 0 to 1023) is initially compressed into a range of 0 to 1000 values so that each data value represents 0.1 percent reflectance and is later compressed so that each value represents 0.25 percent of total reflectance. At this point, all values from 0 to 254 are left alone, while those in the range from 255 to 400 (generally clouds and snow) are recoded to 255. Calibration of the thermal channels (Channels 3, 4, and 5) at EDC used the in-flight coefficients and were converted to relative temperature using the inverse of Planck's equation (Kidwell, 1988) so that each byte value will reflect a 0.5°C change. EDC also geometrically corrected the data to a Lambert Azimuthal Equi-Rectangular Projection with a 1-km² pixel.

Because we did not have cloud-free 1-km resolution data for all South America, a three-year (1986-1988) weekly data set of 15- to 25-km resolution Global Vegetation Index (GVI) data from NOAA (Kidwell, 1988) was utilized in the place of the missing 1-km data. The use of the GVI data accounted for the other 30.4 percent of the final map.

Supplemental information has also been used because of the AVHRR data's coarseness and spectral limitations (J. Brown *et al.*, 1993). Two earlier maps were especially important references: the UN Educational Scientific and Cultural Organization's (UNESCO) *Vegetation Map of South America* at 1:5,000,000 scale (UNESCO, 1980) and *Hueck's Vegetationskarte Von Sudamerika* at 1:8,000,000 scale (1972). Hueck's map describes the "theoretical or potential limits of vegetation and not their actual extent" (UNESCO, 1981). Matthews (1983) has also compiled a vegetation map of South America at 1° by 1° scale. A map of the potential vegetation of South America based on the Holdridge bioclimatic scheme (Holdridge, 1967) provided another independent perspective on land cover.

Many national maps and atlases were compared with the UNESCO map and were used in interpreting the satellite data classification. For a listing, see the atlas and map references. In addition, a complete set of aircraft Operational Navigation Charts (ONCs) were acquired for the continent (U.S. Defense Mapping Agency, various dates). The most comprehensive listing of vegetation maps of South America of which we are aware is in Kuchler (1980).

Analyses

NOAA AVHRR GVI Data

Prior to the analysis of the 1-km resolution AVHRR data, we used the 15- to 25-km resolution GVI data to divide South America into 75 classes (Plate 1). The GVI data, purchased from NOAA, were weekly values of the normalized difference vegetation index (NDVI) covering the years 1986, 1987, and 1988. The vegetation index was created by subtracting Channel 1, or visible red, data from Channel 2, or near infra-red (NIR), data and normalizing it by dividing by their sum (Ch. 2 − Ch. 1)/(Ch. 2 + Ch. 1). NOAA produces these data by selecting the maximum daily vegetation index for each week and retaining it to represent the weekly NDVI. We chose the highest weekly NDVI value for each month and then averaged the three monthly values (1986, 1987, 1988) to minimize the effects of cloud contamination and probable inter-year miscalibration and radiometer drift. NOAA produces weekly NDVI composites for the globe. The data we used were at 15- to 25-km resolution in a Plate Carré projection and extended from 75° N to 55° S latitude.

Classification of the GVI data was based on seasonal changes in the vegetation index or phenology observed in the data. A monthly time series of these data describes a vegetation phenology or seasonality curve. The vegetation index is strongly correlated with vegetation vigor or growth rate (Tucker *et al.*, 1980; Holben *et al.*, 1980). The 75 classes, created with a clustering algorithm (CLUSTR)(ERDAS, 1990; 1991), consisted of pixels with similar vegetation phenology and GVI values. Forty-two classes, covering 94 percent of the continent, were labeled using the UNESCO vegetation map (UNESCO, 1981) as a guide. The remaining 6 percent were labeled unclassified. The yearly phenology information extracted from these data provided a further basis for interpreting the 1-km data. The GVI data were also used to define the land-cover type where cloud-free 1-km data were unavailable.

NOAA AVHRR LAC Data

To create a LAC image suitable for a classification, clouds were removed by screening the thermal and reflectivity data, or by cutting the clouds out of the data with digitized polygon files. We then used a clustering algorithm (ERDAS, 1991) to create an unsupervised classification (see Lillesand and Kiefer, 1979) of 50 to 100 classes in each region. A region was defined as the cloud-free portion of one AVHRR LAC image and was, at most, 1500 km by 1500 km, but never larger than an individual country with the exceptions of the Guyanas (Surinam, Guyana, and French Guiana) which were examined together. More typically, a region was smaller than 1500 km by 1500 km due to the elimination of areas of clouds and smoke. We created 50 classes if the region was small (e.g., the Brazilian state of Rondonia) and contained few remnant clouds or smoke and shadows. We used the larger value, 100 classes, if the region was large or complex (a higher variety of landscapes, topography, and elevations expected). Regions were classified in this way for each available date of LAC imagery.

To characterize a region, we selected, first, the most cloud- and smoke-free LAC images closest to nadir, and, second, the image closest to 1988 with more recent data favored over older data. The regions were generally based on several different classifications of images from different dates, and the process usually resulted in several classifications of a region from different dates. The classifications were superimposed or stitched together in the order worst-to-best so that the best pixels were the last included in the final LAC classification and overwrote any other pixels in the same geographic location.

TABLE 1. CONTINENTAL-SCALE ESTIMATES OF LAND COVER, SORTED BY SIZE.

	sq km	Percent
Tropical Moist Forest and Semi-Deciduous Tropical Moist Forest	5,858,100	33.13
Seasonally Deciduous Woodland (eg. Chaco in Argentina and Cerrado in Brazil)	2,300,100	13.01
Savanna/Grasslands and Pasture	2,296,900	12.99
Secondary Seasonal Forest with Agricultural Activity	979,000	5.54
Cool Deciduous Scrubland (Esp. Argentina)	965,600	5.46
Xerophytic Woodlands (Thornforest or Caatinga in Brazil)	437,200	2.47
Tropical Seasonal or Deciduous forest	368,500	2.08
Agriculture	353,000	2.00
Recently Cleared Tropical Moist Forest	342,700	1.94
Desert	278,900	1.58
Unclassified	275,800	1.56
Montane Degraded Grasslands (Esp. Bolivia and Peru)	271,500	1.54
Degraded Seasonally Deciduous Woodlands	266,700	1.51
Montane Grassland, Tundra or Polar Grassland	263,200	1.49
Degraded Xerophytic Woodlands (Thornforest)	233,600	1.32
Secondary Forest in the TMF region	220,800	1.25
Wet Vegetation (generally mixed water and vegetation)	212,900	1.20
Mixed Pine with secondary forest and agriculture (Southern Brazil)	190,300	1.08
Degraded Grasslands or Grasslands with Agricultural Activity	184,100	1.04
Cool Deciduous Woodlands	173,800	0.98
Montane Degraded Woodlands	166,500	0.94
Water (open)	163,200	0.92
Deciduous Temperate Forest	121,600	0.69
Montane Woodlands	120,800	0.68
Xerophytic Scrubland	115,400	0.65
Seasonally Flooded grasslands (Pantannal)	81,800	0.46
Tropical Open Forest mixed	77,900	0.44
Cool Deciduous Forest	66,600	0.38
Montane Forest	64,100	0.36
Inland Salt Marsh Community	52,700	0.30
Snow and Rock	45,400	0.26
Degraded Tropical Seasonal Forest	39,700	0.22
Tropical Gallery Forests	38,300	0.22
Degraded Temperate Deciduous Forest	29,200	0.17
Tropical Moist Forest with Bamboo (in Acre, Brazil and Bolivia)	13,600	0.08
Mangroves	4,300	0.02
Bare Soil and Rock	3,500	0.02
Urban Regions	2,200	0.01
Xerophytic Littoral Vegetation (Venezuelan Coast)	700	0.00
Montane Degraded Forests	0	0.00
Total	17,680,200	100.00%

Each land cover class defined from the LAC data was labeled according to the following steps:

(1) Determine the mean NDVI of the spectral class.
(2) Determine the relationship between the LAC dates of the NDVI values and the year-long phenology curves as defined from the GVI data.
(3) Compare the spectral class with other map, atlas, or ancillary information. We used all detailed national vegetation maps available, and otherwise referred to the UNESCO (1980) vegetation map. None of the ancillary maps were digital except for the vegetation map of Brazil (IBGE/IBDF, 1988).
(4) Determine if there were recognizable spatial patterns in the LAC data which might indicate agriculture, pasture, or cultural features, such as roads. We used maps and atlases to locate major population centers for each region.
(5) Recode the 50 to 100 spectral classes into a few, generally five or six, important or obvious ones. This step was the most subjective and was largely a function of the analyst's interpretation, guided by the information generated from the preceding steps and the comparison of data across national or state borders.

This process, applied to the 34 LAC satellite tapes of South America, resulted in the creation of 39 land-cover types, plus water and a small unclassified category (Plate 2, Table 1). Ambiguity in labeling, or overlapping among classes, is thought to be most severe where human alterations had been most extensive.

The variety of classification schemes and the differences between classifications based on remotely sensed data and ground-based analyses made direct comparison of the 39 land-cover classes with other continental-scale estimates impossible. Instead, the 39 land-cover classes were consolidated into 13 broader groups (Plate 3, Table 2) which could be compared to general land-cover categories described in other maps. These 13 groups are described below.

The term degraded below is used here as in the UNESCO Map (UNESCO, 1980; 1981). Degraded land includes areas which have been altered or converted from natural or primary vegetation by humans or domesticated animals. For example, because land under conventional agriculture is not in a natural state, all farmland is considered degraded. Changes in the vegetation by indigenous peoples have not been considered.

Group 1. *Intact Tropical Moist Forests* (TMF). Includes Semi-Deciduous Tropical Forests, Tropical Moist Forest with Bamboo,

Plate 1. An unsupervised computer classification of 75 different land-cover groups which are similar in terms of the time of year that the vegetation was active and the amount of vigor of the vegetation. This classification was based on three years of weekly Global Vegetation Index (GVI) data from NOAA. The data have 15 to 25 km resolution. Only the ten largest classes are labeled here.

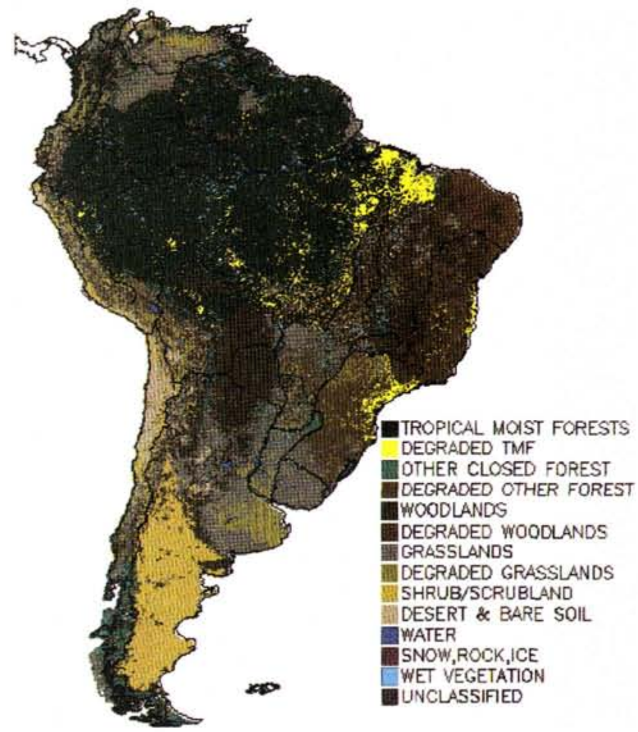

Plate 3. A simplified land-cover map of South America. Here the 39 land-cover classes shown in Plate 2 and listed in the text have been recombined into 13 broader groups as used in Table 2.

Plate 2. A map of the 39 land-cover classes of South America defined from this work. Approximately 70 percent of this map was based on NOAA AVHRR LAC data (1-km resolution), phenology information from the GVI data, and from digital and paper vegetation maps. The remaining 30 percent of the map, predominantly in northeastern Brazil and in montane regions, was created from all the same sources except that there was no LAC data available.

TABLE 2. RESULTS BY COUNTRY OF GENERALIZED LAND-COVER TYPES FOR SOUTH AMERICA FROM THIS WORK.

	Closed Trop. Moist Forest	Re-cently De-graded TMF	Closed Forest	De-graded Closed Forest	Wood-lands	De-graded Wood-lands	Savan-nah, Grass-lands	De-graded Savan-nah, Grass-lands	Scrub-lands, Shrub-lands	Desert, Bare Soil	Water	Snow, Rock Ice	Other	Total
Argentina	1.2	0.0	96.8	0.6	645.4	15.7	755.4	232.8	894.0	37.9	34.0	31.4	35.7	2,779.8
Bolivia	323.5	12.7	409.2	24.6	345.1	102.2	87.7	86.2	4.8	16.5	11.9	0.1	1.1	1,089.4
Brazil	3,522.3	519.7	3,686.0	1,692.2	1,555.9	330.0	740.0	179.4	0.0	0.0	80.9	0.0	124.0	8,388.5
Chile	0.0	0.0	134.1	29.1	75.2	29.8	101.1	14.0	86.9	186.8	7.0	16.6	3.8	684.5
Colombia	581.6	5.4	622.5	11.4	116.3	14.5	255.5	64.0	0.0	0.0	3.1	0.0	22.8	1,110.1
Ecuador	115.5	1.7	121.0	1.7	33.7	4.3	41.9	13.3	3.2	2.5	0.6	0.0	0.8	223.1
Fr. Guyana	78.8	0.0	79.8	2.4	0.6	0.0	0.2	0.0	0.0	0.0	0.1	0.0	1.0	84.1
Guyana	159.4	2.0	171.6	2.4	5.4	0.3	18.4	1.5	0.0	0.0	1.2	0.0	3.7	204.3
Paraguay	0.3	0.0	8.9	0.2	209.1	50.7	104.0	26.5	0.0	0.0	0.6	0.0	1.1	401.1
Peru	620.8	19.1	654.7	19.1	88.0	78.8	139.0	97.4	64.3	88.0	8.3	0.7	5.6	1,244.1
Surinam	126.0	2.5	128.5	10.0	0.5	0.3	1.2	0.4	0.0	0.0	1.1	0.0	3.3	145.2
Uruguay	1.4	0.0	2.1	0.0	0.9	0.0	154.1	11.0	0.0	0.0	3.0	0.0	5.9	177.0
Venezuela	379.1	0.2	415.5	9.9	33.9	40.2	243.3	82.0	27.2	0.0	11.4	0.0	8.4	871.8
Unclassified														313.0
Total	5,909.9	563.4	6,530.7	1,803.7	3,109.8	666.9	2,642.0	808.5	1,080.6	331.7	163.2	48.9	217.2	17,716.1
Continent	33.4%	3.2%	36.9%	10.2%	17.6%	3.8%	14.9%	4.6%	6.1%	1.9%	0.9%	0.3%	1.2%	100.0%
Category		8.7%		21.6%		17.7%		23.4%						

N.B. All Values in 1,000s of Sq. Km. or Pct.
"TMF" includes Tropical Moist, Semi-deciduous and Gallery Forests
"Grasslands" includes those seasonally flooded
"Closed forest" includes TMF, Montane forests, Cool and Temperate Deciduous Forests and Tropical Seasonal Forests
"Degraded grasslands" includes Agriculture
"Desert, Bare Soil" includes inland Salt Marsh Communities
"Other" includes wet vegetation and mangroves

and Tropical Gallery Forests. These vegetation covers have high vegetation vigor throughout the year and all are considered to be closed canopy forests. This includes forests of the Amazon Basin and the coastal forests of Colombia and Ecuador. As intact tropical moist forests are also closed canopy forests, this group is a sub-set of Group 3.

Group 2. *Degraded Tropical Moist Forest* (TMF) and Secondary Forest in the TMF zone. Includes large blocks of cleared forest surrounded by, and both spectrally and visually distinct from, intact tropical moist forest. These clearings do not include areas recognized as agricultural land or pasture. As more clearing occurs and as older clearings are abandoned to secondary regrowth, the distinction becomes less well-defined. Thus, this estimate of secondary forest is likely an underestimate. We assumed that the observed patterns of cleared forest were relatively recent and probably had occurred within the last 10 years as older clearings may have reverted to secondary forest. Secondary forest canopy closure in 5 to 15 years is common in the tropics (Jacobs, 1981). This group includes degraded forest land in the Amazon Basin, along the Pacific coast of Colombia, and large areas along the Brazilian Atlantic coast. As degraded tropical moist forests are also degraded closed canopy forests, this group is a sub-set of Group 4.

Group 3. *Intact Closed Forest.* Includes all of Group 1 as well as Tropical Seasonal or Deciduous Forest, Montane Forest, and Cool Deciduous Forest and Deciduous Temperate Forest. The Montane Forests occur along the eastern slope of the Bolivian and Peruvian Andes, while the Temperate and Cool Deciduous Forests occur along the Argentinean and Chilean Andes. All the deciduous forests have a relatively high vegetation vigor during part of the year. We made this category because other classifications of forests of South America include closed forest as a distinct category.

Group 4. *Degraded Closed Forests.* Includes all of Group 2 as well as Degraded Deciduous Temperate Forest, Secondary Seasonal Forest with Agricultural Activity, Urban Zones, Degraded Tropical Seasonal Forest, and Mixed Pine with secondary forest and agriculture. Most of these categories were defined based on information from either the Brazilian vegetation map (IGBE, 1988) or the UNESCO (1980) map.

Group 5. *Intact Woodlands.* Includes Seasonally Deciduous Woodlands, Xerophytic Woodlands, Montane Woodlands, Cool Deciduous Woodlands, and Tropical Open Forest Mixed. The Seasonal Deciduous and Xerophytic Woodlands include the coastal thornforests; the Gran Chaco of Argentina, Bolivia, and Paraguay; and the Cerrado of central Brazil. The Montane and Cool Deciduous Woodlands occur primarily along the Andes. Typically, these vegetation types have a short growing season and are moisture limited.

Group 6. *Degraded Woodlands.* Includes Degraded Seasonally Deciduous Woodlands, Degraded Xerophytic Woodlands (Thornforest), and Montane Degraded Woodlands. This group includes the degraded thornforests of Venezuela, the degraded lands of the Cerrado and Gran Chaco, and degraded Andean woodlands. Degraded lands in the Gran Chaco were identified as large rectangular clearings in an otherwise uniform area and were likely pasture. Many other categories were defined from the Brazilian vegetation map (IGBE 1988), the UNESCO (1980) map, or by pattern recognition.

Group 7. *Intact Grasslands.* Includes Savanna Grasslands and Pasture, Seasonally Flooded grasslands (Pantanal), Montane Grasslands, and Tundra or Polar Grasslands. These include the Pampas of Argentina and Uruguay, the Beni of Bolivia, the Llanos of Colombia and Venezuela, and some portions of the Altiplano of Bolivia and the Puna of Peru.

Group 8. *Degraded Grasslands.* Includes Agriculture, Grasslands with Agricultural Activity, and Montane Degraded Grasslands. Most agriculture was defined with the UNESCO map and on numerous Landsat satellite photos of the Parana, Paraguay, and Rio de la Plata river system. Large areas of agricultural land oc-

cur in the Pampas of Argentina and northern Venezuela. Savannah mixed with agricultural land occur primarily in the Cerrado of central Brazil.

Group 9. *Shrub and Scrublands.* Includes Xerophytic Scrubland, Xerophytic Littoral Vegetation, and Cool Deciduous Scrubland, generally in Patagonia or along the dry coasts of Peru, Chile, and Venezuela. These areas have short, weak growing seasons limited by rainfall or by cold.

Group 10. *Desert, Bare Soil, or Inland Salt Marsh Communities.*

Group 11. *Open Water.*

Group 12. *Snow, Rock, and Ice.*

Group 13. *Other:* Wet Vegetation (mixed water and land pixels) and Mangroves.

and *Unclassified*

Results and Discussion

Continental-Scale Estimates of Land Cover

Both country level and continental-scale summations for the 39 land cover types were generated from the map (Plate 2). Because of the inherent geometric distortion in the original map projection, particularly in the higher latitude zones of Argentina and Chile, the map projection of the final product was converted to a Lambert Azimuthal Equal Area projection.

Table 1 shows estimates of the 39 land-cover classes for South America ranked by size. Because few other sources examine all countries in South America, it was difficult to compare continental sums. The only other study that includes all countries and can be directly compared to our data is an FAO report (1985). The FAO estimated that forests and woodlands covered 9.29 million km², slightly lower than our 1988 estimate of 9.64 million km². Our estimate includes more woodland and less grassland than the FAO (1985).

We found that about 22 percent of all closed forests, including tropical moist forests, had been altered, cleared, or degraded by the date of imagery used. By comparison, Houghton *et al.* (1991) estimated that 25 percent of the forests of South and Central America and Mexico had been cleared since 1850. We found nearly 1,800,000 km² of closed forest has been lost, converted, or degraded. The vast majority of these losses occurred along the Brazilian coast, which has been heavily occupied since colonial times. According to Peters and Lovejoy (1990), only 7 percent of the original 1,000,000 km² of the Brazilian Atlantic tropical moist and seasonal forests and the Araucaria forests of the uplands of southern Brazil remain forested, and only 1 percent remain undisturbed. About 563,000 km², or 31 percent of the alteration of closed forests for South America has occurred in the tropical moist forests and semi-deciduous forests largely of Brazil. This change represents about 9 percent of the tropical moist forests of South America (Group 1) (Table 2).

The loss in woodland area represents a decline of about 18 percent, or about 700,000 km² of the original area. The majority of these changes have occurred in Brazil (50 percent of the loss), Bolivia (15 percent), Peru (12 percent), and Paraguay (8 percent).

The second largest category of loss or conversion has been in the savannah-grasslands. Here a decline of about 23 percent represents a change of some 810,000 km² to other uses or a conversion to wasteland. About 30 percent of these changes have occurred in Argentina and about 22 percent in Brazil. The countries of Peru, Bolivia, Venezuela, and Colombia account, respectively, for 12 percent, 11 percent, 10 percent, and 8 percent of these changes in original savannah-grasslands.

Country-Level Estimates of Land Cover

Estimates of the area of each land-cover group by country appear in Table 2. Total area of closed forest and the area of cleared tropical closed forest are also shown. According to this analysis, Brazil has lost or altered the largest absolute area of tropical forest of any nation in South America and the largest fraction of its once-forested area. Our estimates are that 31 percent of Brazil's original closed forests, including seasonal forests, have been cleared, degraded, or otherwise altered. The IBDF (1982) vegetation map of Brazil indicates that 29 percent of the forested areas of Brazil are now either degraded forest, secondary forest, pasture, or agriculture. The area of tropical moist forest cleared in Brazil (12 percent) includes segments of the Atlantic Coastal Forest that could have been described as "moist" and "tropical." Mahar (1989) determined that 12 percent of Brazilian "Legal Amazonia," which includes the states of Amazonas, Para, Rondonia, Acre, Mato Grosso, Roraima, and Amapa, had been deforested by 1988. The most recent estimate indicates a loss of 230,000 km² of closed forest and some 587,000 km² of closed forest "adversely affected" (Skole and Tucker, 1993) up to 1988 in Brazil's "Legal Amazonia." We estimate some 317,000 km² of closed forest cleared, about 8.4 percent of the total closed forest of "Legal Amazonia."

Summation of the total degraded land in all categories by country still yields Brazil as the nation in South America that has most altered its natural land cover. Some 27 percent of Brazil's total area has been cleared, planted, altered, or degraded. A similar calculation for Bolivia and Paraguay yields about 20 percent alteration and for Venezuela and Peru about 15 percent altered or degraded. From this work, the nations that had least altered their natural land cover were French Guiana and Guyana, with 2 to 3 percent alteration.

Intercomparisons and the Reliability of Results

Internal Comparisons

A comparison of our map with ground reference data would thoroughly test the reliability of our classification. There is no ground reference data for an area this large, however, and no continental-scale map that is necessarily more accurate than the one that we have produced. Undoubtedly, some of the national-scale maps (e.g., Venezuela, by Huber and Alarcon (1988)) are more accurate than the map produced here and could be used to appraise accuracy at the national scale. But, even such a national comparison would require maps not only in digitized form but with similar classification schemes. We did not have access to such maps, if they exist, and instead appraised the accuracy of the South American map through a series of other internal and external comparisons. We examined the variation in information sources used to develop classifications within our map, compared other estimates of the areal extent of land-cover classes to our findings, and compared our class assignments in a widely distributed set of ground sites described in the literature.

In order to appraise which parts of the continental map were most and least reliable, we developed reliability ratings for all country-level classifications (Table 3a) and for the nation-sized states and area within Brazil (Table 3b). Three categories of data, LAC data quality, GVI data quality, and ancillary map data quality, were rated by assigning values from 0 to 10 (worst to best). For LAC data, distance from the nadir of the image(s), smoke and haze content, age of the data, presence of shadows, and data noise were rated with the 0 to 10 scale, and then multiplied by the percentage of

Table 3a. Estimates of the Reliability of Regional Classifications in Brazil

Brazilian States and regions	Sq. Km	Percent of Country	Reliability Rating	Area Weighted
Acre	153,698	1.81	0.97	0.017
Amapa	142,359	1.67	0.92	0.015
Amazonas	1,567,954	18.42	0.68	0.124
Bahia w/Minas Gerais, & Piaui, RdJ, Espirito Santo	1,494,262	17.55	0.75	0.132
Goias	345,960	4.06	0.91	0.037
Maranhao	329,556	3.87	0.87	0.034
Mato Grosso	901,421	10.59	0.91	0.097
Northeast States	408,197	4.80	0.45	0.022
Para	1,246,833	14.65	0.69	0.101
Mato Grosso Do Sul	357,472	4.20	0.92	0.039
Rio Grande Do Sul	280,674	3.30	0.86	0.028
Rondonia	238,379	2.80	0.91	0.026
Roraima	225,017	2.64	0.77	0.020
S. Paulo, St. Catar., Parana	542,898	6.38	0.93	0.059
Tocantins	277,322	3.26	0.90	0.029
	8,512,002	100.00%	0.83 Mean	0.78 Weighted Mean

the area covered by LAC data. For the GVI data, ratings were assigned to whether or not the area was classifiable with the GVI data and whether the classification covered a large or small area. For the ancillary map data, the quality of the relevant national map or atlas, the similarity of the national map's vegetation classification scheme to the scheme developed in this work, and the age of the national map or atlas, were all rated from 0 to 10. Using the extremes in each of the three categories results in ratings of 0.0 and 1.0. Each of the three categories was weighted so that the quality of the LAC data was responsible for 50 percent, the GVI classification was responsible for 10 percent, and the national map or atlas was responsible for 40 percent of the score.

Reliability ratings for individual countries ranged from a low of 0.45 and 0.47, respectively, for Ecuador and Argentina. For both of these countries, the available maps were poor and there was incomplete LAC data. The imagery for Ecuador, in particular, was very cloudy, off nadir, and, because of mountainous terrain in much of Ecuador, poorly resolved with the GVI data. The highest ratings, 0.79, 0.79, and 0.78, were determined for our maps of Bolivia, Paraguay, and Brazil. These higher values were resulted in part from excellent LAC coverage of all three countries and, in the case of Brazil and Bolivia, from high quality vegetation maps or atlases. Brazil was the only country in South America for which we had a digital vegetation map.

Table 3b. Estimates of the Reliability of Country Classifications of South America

Country	Sq. Km	Percent of Continent	Reliability Rating	Area Weighted
Argentina	2,766,900	15.54	0.47	0.074
Bolivia	1,098,585	6.17	0.79	0.049
Brazil	8,512,001	47.80	0.78	0.374
Chile	756,630	4.25	0.60	0.025
Colombia	1,138,919	6.40	0.65	0.041
Ecuador	283,561	1.59	0.45	0.007
Fr. Guiana	91,000	0.51	0.56	0.003
Guyana	214,970	1.21	0.56	0.007
Paraguay	406,754	2.28	0.79	0.018
Peru	1,285,220	7.22	0.65	0.047
Surinam	163,266	0.92	0.56	0.005
Uruguay	176,216	0.99	0.69	0.007
Venezuela	911,975	5.12	0.60	0.031
	17,805,996	100.00%	0.63 Mean	0.69 Weighted Mean

We also compared the areal extent of land-cover classes to those of Matthews (1983) who used 15 land-cover categories. Again, because of different categories of land cover, we could not directly compare our digital map with Matthews, but, by recombining categories into similar groups, a continent-wide comparison was possible (Table 4). The largest differences occurred in the woodland and savannah categories. Our map yielded higher estimates of woodland area (22 percent versus 12 percent of the continental area) and smaller estimates of grasslands (20 percent versus 28 percent of the continental area) than did Matthews (1983). The differences were similar to those found between Matthews (1983) and in other studies (Olson *et al.*, 1983) and likely reflect the difficulty of discerning, based on low resolution satellite data, where savannah grasslands end and where woodlands begin. Although these differences highlight areas of disagreement between the two maps, they do not measure the actual accuracy of either map.

Ground Study Comparison

The accuracy of the classification system used in the creation of the digital land cover map was assessed by comparing class assignments to ground studies (Adamoli *et al.*, 1990; Adis *et al.*, 1979; Ambrosetti *et al.*, 1986; Batista *et al.*, 1988; Bernhardson, 1986; Boom, 1986; I.F. Brown *et al.*, unpubl. ms., 1993; Bucher, 1982; Buschbacher *et al.*, 1987; Cabido and Acosta, 1986; Jordan *et al.*, 1982; Cimino *et al.*, 1986; Clusener and Breckle, 1987; D'Angelo *et al.*, 1987; Denevan and Padoch, 1987; Diaz and Acosta, 1989; Eden and Andrade, 1988; Emory, 1990; Fearnside and Keller, unpubl. data, 1990; Haase, 1989; Jonkers and Schmidt, 1984; Jordan, 1985; Leon and Aguiar, 1985; Lewis *et al.*, 1990; Lewis, 1986; Maos, 1985; Martinez, 1982; Matteucci, 1987; Menghi *et al.*, 1989; Monasterio, 1986; Morales and Pacheco, 1986; Pires, 1978; Poels, 1987; Ralph, 1985; Russell, 1987; Saldarriaga, 1987; Van der Hammen and Cleef, 1986; Veblen *et al.*, 1980; Vieira *et al.*, unpubl. ms., 1993; Wilcox *et al.*, 1986;

Table 4. Estimates of Land Cover by Matthews (1983) and this Study.

	Matthews		This study	
Closed (+ Degraded) Tropical Moist Forest	6,845,708	38.87%	6,473,300	36.61%
Intact (+ Degraded) Closed Forest	8,782,366	49.87%	8,334,400	47.14%
Woodlands (+ Degraded)	2,156,957	12.25%	3,776,700	21.36%
Savannah/Grasslands (+ Degraded)	4,878,049	27.70%	3,450,500	19.52%
Shrublands	1,759,104	9.99%	1,080,600	6.11%
Desert	34,524	0.20%	331,700	1.88%
Other			393,100	2.22%
Unclassified			313,000	1.77%
Total	17,611,000 sq km	100.0%	17,680,000 sq km	100.0%

TABLE 5. ACCURACY TEST FOR LAND-COVER CLASSES

Percent R* Area Correct	Total R* Area Tested	Percent R* Area in Total Class	Total No. sites	No. sites correct	Class #	Class Descriptions
100.0	10,073	2.94	9	9	102	Cleared TMF
100.0	549	0.32	8	8	135	Cool Deciduous Woodlands
100.0	2,735	1.24	7	7	111	Secondary TMF w/Agriculture
100.0	543	0.82	5	5	136	Cool Deciduous Forest
100.0	89	0.20	4	4	137	Snow/Rock
100.0	1,613	0.59	4	4	130	Degraded Montane Grasslands
100.0	1,239	0.74	3	3	131	Montane Woodlands Degraded
100.0	122	0.31	3	3	123	Degraded Tropical Seas. For.
100.0	84	0.01	3	3	121	Secondary Seasonal For. w/Agriculture
100.0	571	1.49	2	2	115	Gallery Forests
100.0	45	0.06	2	2	116	Tropical Open Forests (mixed)
100.0	25	0.07	1	1	140	Degraded Temp. Decid. Forest
100.0	339	0.15	1	1	120	Degraded Xerophytic Woodlands
100.0	191	0.16	1	1	128	Montane Woodlands
100.0	3	0.001	1	1	141	Temperate Decid. Forest
99.9	1,075	0.41	8	7	127	Montane Grassland
96.0	1,026	0.28	11	10	113	Tropical Seasonal or Decid. Forest
100.0	512	0.31	15	14	104	Water
92.8	1,314	0.14	14	13	133	Cool Deciduous Shrublands
100.0	16,608	0.72	33	27	105	Savanna/Grasslands
82.5	54,893	0.94	27	24	101	Trop. Moist & Semi-deciduous Forest
89.8	805	0.70	8	6	125	Xerophy. Scrubland
93.5	15,182	0.66	29	26	109	Seas. Decid. Woodlands
95.2	4,628	1.74	14	10	117	Cerrado (Woodlands) degraded
98.0	638	0.18	9	8	114	Agriculture
45.9	357	0.44	11	4	112	Seasonally flooded Grassland
55.0	894	0.20	10	6	119	Xerophy. Woodlands
64.6	407	0.15	4	2	139	Desert
100.0	1,135	0.53	24	19	106	Wet Vegetation / Mixed
7.1	14	0.01	2	2	118	Grasslands or Sav. w/Agriculture
15.9	63	0.10	3	1	138	Salt Marsh Community
0.0	9	0.21	4	0	108	Mangroves

R* area refers to the total number of pixels. Each pixel = 1 km². In some cases (eg. Class 104) not all sites were classified correctly yet the percent area correct is still 100% due to round off. In other words, the incorrect test areas were too small to affect the percent correct when reported to 1 decimal point. Overall accuracy for the final map from this analysis was estimated to be 90%. This is calculated by: summation [(percent area of class correct) × (percent class in total map)] for all classes.

Woodwell *et al.*, 1986). Studies based upon ground data collected within the last 12 years were selected. Other areas, where land-cover and land-use descriptions from at least three map-independent sources were in agreement, were also selected. Selected areas were digitized into vector files and superimposed on the digital South America map. Land-cover descriptions from the literature and reference maps were compared to the class assignments in the South America map for each site selected. The class assignments were either accepted or rejected, according to whether or not the class was in agreement with the land-cover types described in the references. The study sites varied considerably in size, from 33 km² to 29,000 km², but each comparison was equally weighted.

Fifty-six ground reference data sites were located. Thirty-one additional sites were located from independent maps and country atlases. Study or test sites were identified throughout the map area. Thirty-three of the 39 land-cover type classes encompassing 98.4 percent of the mapped area, were represented by test sites. Although these study or test sites covered only 0.67 percent of the total map area, we were able to make repeated tests on over two-thirds of the land-cover type classes of the digital map. The largest classes, numbers 101, 105, 133, 109, and 121, which cover 69 percent of the map, were each tested in at least eight study sites.

The decision to accept or reject the digital map class assignments in each study site was the most subjective step in this analysis. Those land-cover types clearly unrelated to the ground study descriptions were immediately rejected. However, many test sites described a mosaic of land-cover types, and offered little information on the land-cover type distributions within the study area. In such cases, all land-cover types reported to occur in the site were accepted, regardless of their abundance or distribution. This process undoubtedly resulted in an overestimate of accuracy. Some land-cover types which tend to occur together, such as tropical moist forest with and without shifting cultivation, and savannah with and without grazing, were frequently described (and therefore accepted) within the same study areas. Thus, the ability of this classification system to distinguish between closely related categories was not thoroughly tested.

We determined that 90 percent of the test areas were considered correctly classified (Table 5). Twenty-four of the 33 tested digital map classes were correctly assigned in over 90 percent of the test areas. These 24 classes cover 85 percent of the map, while those classes which proved less than 75 percent reliable covered only 6.5 percent of the mapped

area. The remaining 8.5 percent were between 76 percent and 89 percent accurate.

Conclusions

The continental-scale digital map of South America presented here, based on 1-km resolution satellite data, improves by an order of magnitude the resolution of existing available continental land-cover maps. Similar 1-km resolution products could be produced for all areas of the world with defined accuracies if higher resolution satellite data such as those from Landsat or SPOT data were used to assess accuracy through sampling. The individual classifications were objective, based on digital data from the NOAA AVHRR satellites. Thus, classification was relatively consistent from country to country. The classification was based on numeric measures of vegetation vigor, which is related to leaf cover and rate of growth. Visual pattern analysis and interactive examination of continental and national scale vegetation maps, together with numerical data on elevation, and phenology, as determined by the satellite data, were used to assign names to the classes. The digital map can be easily updated as new satellite data become available, and its format facilitates modeling applications. Digital copies of the map are available from the authors.

Thirty-nine land-cover vegetation types were obtained for the continent and estimates of more generalized land-cover groups were determined for each country of South America. We estimate that 9 percent of the closed tropical moist forests of South America had been cleared recently, in the last ten years, that 22 percent of the original closed forests of South America had been cleared or degraded, and that 18 percent and 25 percent of the original woodlands and grasslands, respectively, had been cleared or degraded.

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